Hot-Electron-Induced Degradation of Metal-Semiconductor Field-Effect Transistors

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Abstract—Hot-electron trapping in the SiN passivation was found to be a cause for gradual degradation during RF operation of metal-semiconductor field-effect transistors. The time dependence and threshold energy for trap formation was determined by dc and electro-luminescence tests. The spatial distribution of trapped electrons was directly observed by a novel high-voltage electron-beam-induced-current imaging technique. Argument was also made for trapping in the SiN instead of at the GaAs/SiN interface.

I. Introduction

It is well-known that hot electrons can be trapped in the gate oxide of a Si MOSFET causing its threshold voltage to shift. For a GaAs MESFET, hot electrons can also be trapped in the SiN beside the gate (Fig. 1), thereby decreasing the MESFET's transconductance without affecting its threshold voltage (Fig. 2). The hot electrons are generated by biasing the MESFET with a high drain voltage and driving it into deep gain compression. Under such stresses, the so-called "power slump" phenomenon occurs which can be characterized by approximately 1 dB reduction in output power over 1 000 h of RF operation. Frequently confused with other dc or thermal stress effects, this phenomenon has not been reported until recently [1]-[3]. Using a novel RF waveform probing technique [4], we concluded that power slump was dependent on the peak drain-gate voltage (V_{DG}), which led to the development of an accelerated on-wafer dc screening test [5]. In this paper, we report in-depth investigation of the physical mechanism for power slump.

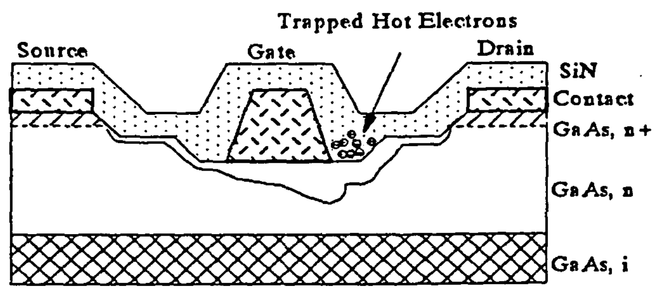

Fig. 1 Schematic cross-section of a slumped MESFET.

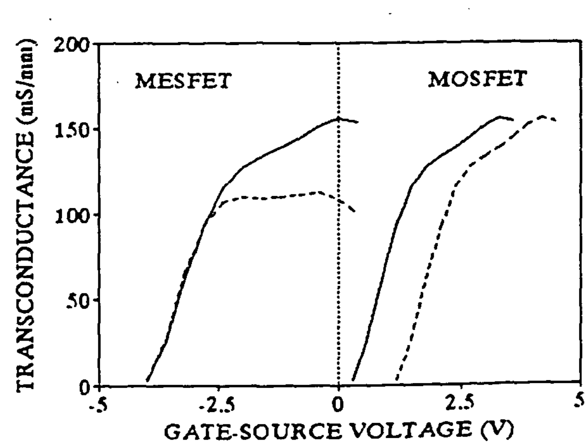

Fig. 2 Hot-electron effects on MESFET and MOSFET characteristics. (—) before; (---) after.

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II. Results and Analysis

Experimental data of Si-implanted, SiN passivated, 0.5 μm gate MESFETs from the same GaAs wafer are presented in the following. Figure 3 shows the dc and RF drain characteristics of a MESFET that has slumped. It can be seen that, with stress, the knee voltage increases while the drain current decreases, resulting in contraction of the RF trajectory hence the output power. Figure 4 shows that, based on approximately 100 MESFETs that have been dc or RF (8 GHz) stressed, comparable slump behavior can be obtained within 24 h albeit at different threshold V_{DG}. The RF threshold is higher than the dc threshold because, under RF, the MESFET spends little time at peak V_{DG}.

Figure 5 shows that, as measured by fractional change in the open-channel current (I_{MAX}), the slump rate is approximately proportional to the square root of time. Such a gradual saturation behavior can be explained based on the build up of retarding field by the trapped hot electrons. According to our two-dimensional numerical simulation [6], the trapped electrons gradually reduces the maximum field in the MESFET channel even under constant V_{DG} stress.

Analytically, the impact-ionization-induced gate current of a MESFET is expected to depend inverse-exponentially on the maximum field. Figure 6 shows that this is indeed the case for $V_{DG} > 10$ V where the gate current is dominated by impact ionization. By comparing the slope of the gate current before and after slump, the maximum field was found to be reduced. Further, one would expect the reduction of the maximum field and channel current to both depend linearly on the accumulation of hot electrons. Figure 7 verifies such a r lationship between the change in gate and drain currents.

The ratio of threshold energy for electron trapping vs. that for impact ionization can be obtained by plotting the slump lifetime against the stress current on logarithmic scales. Here the MESFET lifetime is determined by the time it takes for I_{MAX} to drop a certain fraction, say, 10%. From Fig. 8, electrons as hot as 1.9 eV was necessary to cause the MESFET to slump.

Recently, we found a correlation between power slump and visible electro-luminescence [7]. Under high V_{DG} and with the MESFET pinched off, the spectrum contains, in addition to the bandgap transition of 1.4 eV, 1.7, 1.9 and 2.2 eV peaks (Fig. 9) which correspond to impact ionization thresholds of $\langle 110 \rangle$ electrons in GaAs [8]. The fact that electro-luminescence was found to be a precursor for power slump supports the above finding that the power slump threshold energy is slightly higher than that of impact ionization. Figure 10 shows that the total electro-luminescence intensity is proportional to the impact-ionization-dominated gate current under high V_{DG}.

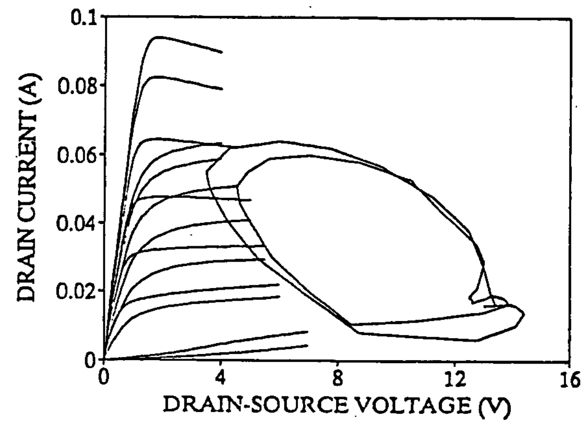

Fig. 3 Dc and RF drain characteristics of a MESFET. At dc, V_{GS} = 0.8, 0.5, 0, −0.5, −1.0, −1.5 and −2.5 V. RF, V_{GS} = −1.5 V, V_{DS} = 10 V. (—) before, (---) after slump.

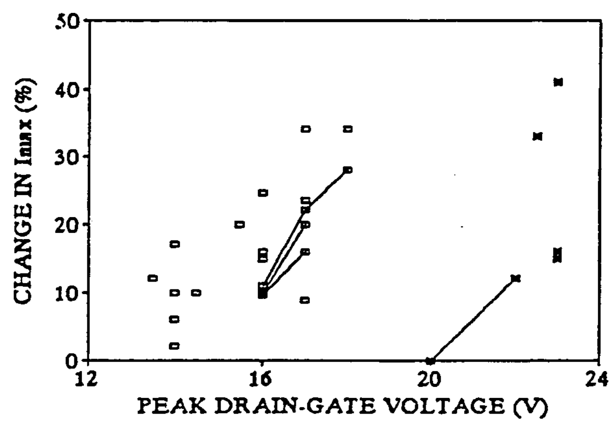

Fig. 4 (□) dc and (×) RF threshold drain-gate voltages for power slump within 24 h. Line indicates repeated experiments on the same transistor but at different voltages.

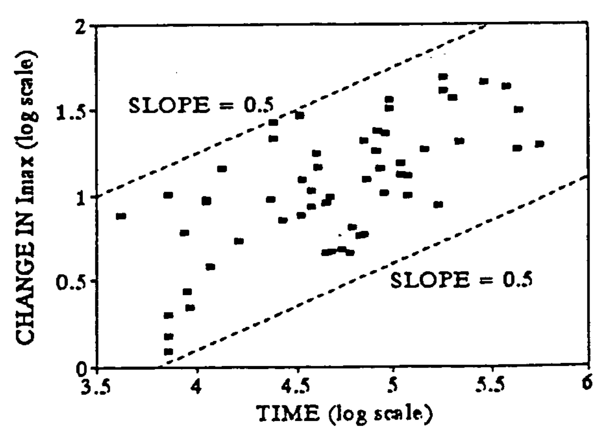

Fig. 5 Rate of slump in open-channel drain current.

The increased surface depletion by the retarding field of the trapped electrons was directly observed by a novel high-voltage electron-beam-induced-current (HV-EBIC) imaging technique [9]. Figure 11 compares the top-view images by SEM and HV-EBIC, respectively, of the gate region of a slumped MESFET. The SEM image confirms that the MESFET geometry is symmetrical w. r. t. the source and drain. However, the HV-EBIC image shows that, due to localized electron trapping, the depletion region extends 0.1 μm farther from the gate toward the drain than from the gate toward the source.

III. Discussion

It is conceivable that, similar to the case of MOSFET, hot electrons are trapped at the GaAs-SiN interface instead of in SiN. However, observations to date support the latter, probably because the interface state density of GaAs is very high in any case. The observations include: (i) The type of passivation material matters, but not the deposition method. (ii) Hot-electron-induced traps have a time constant of the order of 10 μs while typical interface states ~ 1 μs. (iii) The threshold energy for power slump is significantly higher than the bandgap of GaAs. (iv) Once the MESFET slumps, it cannot recover by deep UV irradiation or 200°C anneal which are known to affect the interface states. (v) Partial recovery was found after partial etching of SiN. (vi) Although the recovery was incomplete after complete etching of SiN, etching damage on both the source and drain sides of the channel was revealed by HV-EBIC.

IV. Conclusion

In summary, power slump of MESFETs was attributed to hot-electron trapping in the SiN passivation. A square-root time dependence and a threshold energy of 1.9 eV was determined experimentally and found consistent with electro-luminescence measurements. The localized electron trapping near the drain end of the gate was directly observed by HV-EBIC. The above findings led to a fundamental understanding of the power slump mechanism, based on which a systematic trade-off between power, efficiency and reliability of the MESFET can be achieved.

Acknowledgment

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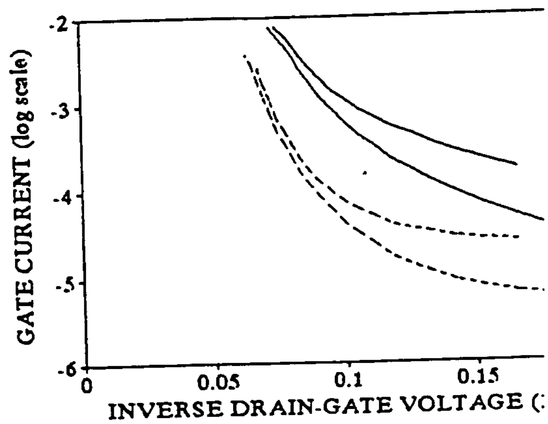

Fig. 6 Reverse gate current (—) before and (---) after sl V_{GS} = −5 and −6 V bottom up.

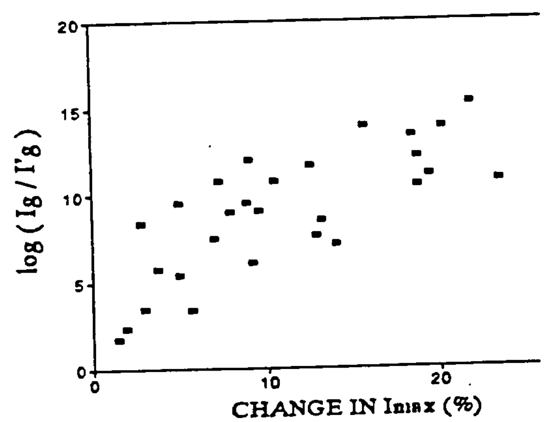

Fig. 7 Change in gate current vs. that in open-channel dra (I_G) before, (I'_G) after.

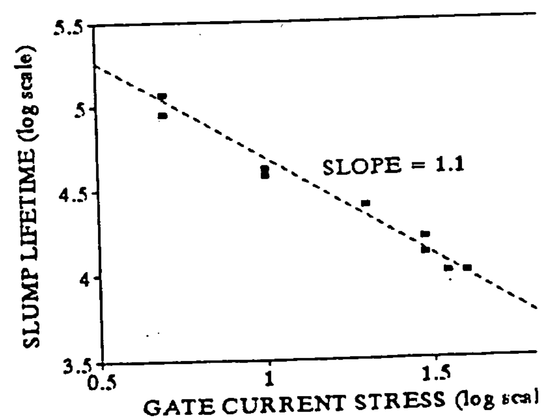

Fig. 8 Slump lifetime vs. gate current stress.

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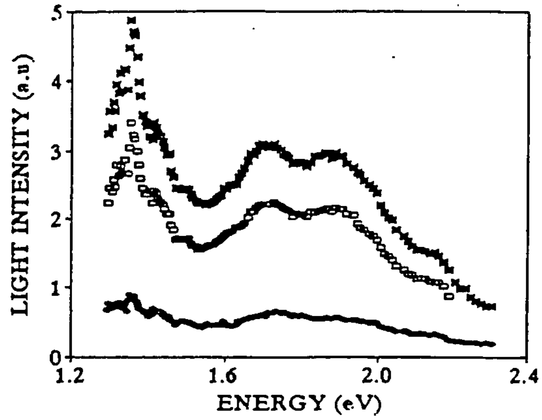


Fig. 9 Pinched-channel electro-luminescence spectrum.

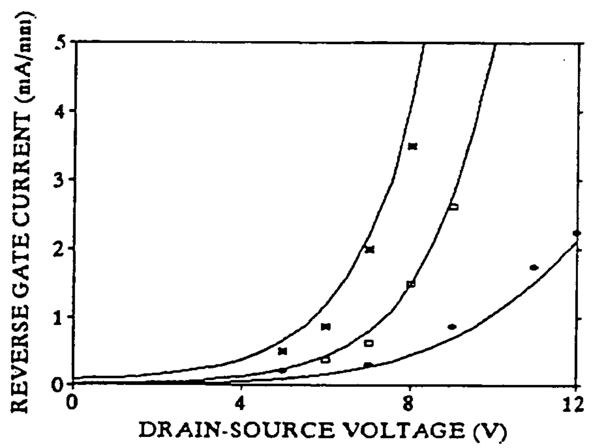
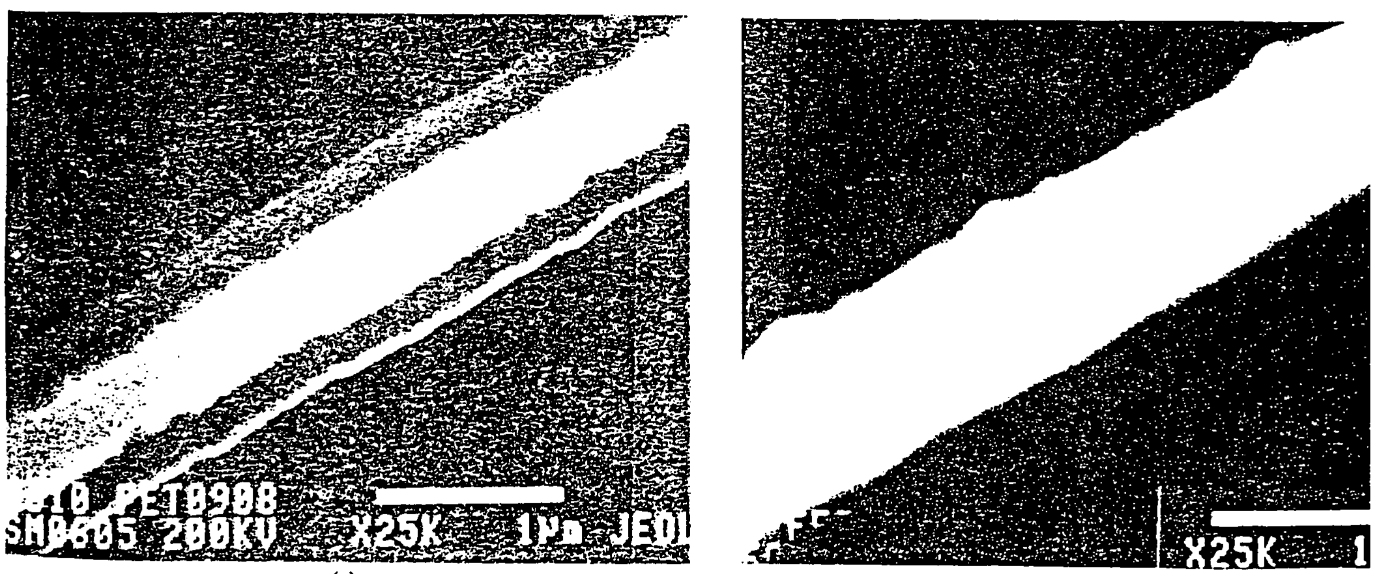


Fig. 10 (Lines) total electro-luminescence intensity and (symbol reverse gate current. V_{GS} = (×) −6, (□) −5 and (+) −4 V.



(a)

(b)

Fig. 11 (a) SEM and (b) HV-EBIC top-view images of the gate region of a slumped MESFET.